

Estimating the Value of Offshore Wind Along the United States' Eastern Coast

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Overview

Development of offshore wind in the United States has been limited to date despite a recent acceleration in global deployments and indications of steep cost reductions in European tenders for offshore wind energy. In part, limited US growth is due to an unclear understanding of the economic *value* that offshore wind provides within local or regional electricity markets. One reason for this lack of clarity is due to the fact that offshore projects can be developed in many different locations, and that diurnal and seasonal wind resource profiles vary by project location. Differences in location and location-specific generation profiles can affect the value of wind power in terms of which other generators wind displaces (and hence both the type and quantity fuels and emissions that wind power reduces), wind's contribution to meeting peak demand, and the local price of electricity and renewable energy credits (RECs) that wind earns.

With these and other value components in mind, this project explores a hypothetical question: What would the marginal economic value of offshore wind projects along the east coast of the United States have been from 2007-2016, had any such projects been operating during that time period? Using historical weather data at thousands of potential offshore wind sites, combined with historical wholesale market outcomes and REC prices at hundreds of possible interconnection nodes, we develop a rigorous method to answer this question, focusing mostly on the marginal economic value but also including environmental impacts. We consider energy, capacity and REC value, avoided air emissions, the wholesale price 'merit-order' effect, and natural gas price suppression. In addition to assessing each value component, and how value has varied geographically and over time, we also evaluate value differences between offshore and onshore wind, the 'sea-breeze' effect, the capacity credit of offshore wind, the value of interconnecting at and selling to different locations, the incremental value of storage, and the impact of larger rotors and taller towers. We then go on to discuss, at a high level, various factors that might drive these value components higher or lower in the future, as offshore wind deployment commences.

This work builds on and complements recent and ongoing research by NREL, and is informed by a comprehensive review of the available offshore wind energy valuation literature. Although the historical nature of this analysis limits its applicability going forward, knowing how the historical value of offshore wind has varied both geographically and over time, and what has driven that variation, can nevertheless provide important insights to a variety of stakeholders, including wind developers, purchasers and energy system decision-makers. In addition, focusing on market value may help to inform the U.S. DOE on its offshore wind technology cost targets, as well as the early-stage R&D investments necessary to reach them.

Data and Methods

We used NREL's [Wind Toolkit](#) to identify potential offshore wind sites along the U.S. eastern seaboard (from Maine to northern Florida, and inclusive of both potential fixed-bottom and floating-platform sites), excluding those sites that are insufficiently windy or are in especially-deep or non-US

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waters. The Wind Toolkit provides estimated hourly wind speeds at each of the resulting 6,693 sites from 2007-2013. To extend that hourly dataset through 2016, we relied upon a global meteorological simulation (MERRA reanalysis), using a site-by-site linear regression method to “downscale” the coarser MERRA data to site-specific hourly wind speeds for 2014-2016. Wind speed is then converted to wind power using a representative power curve for a 6-MW turbine with a 155 meter rotor (yielding a ‘specific power’ rating of 318 W/m²) and a hub height of 100 meters. Net output assumes 96% availability and includes assumptions for wake, electrical, and other losses that can vary by site and hourly wind speed.

Each offshore wind site that falls within one of the three organized Independent System Operator (ISO) markets along the coast—i.e., ISO New England (ISO-NE), the New York ISO (NYISO), or the PJM Interconnection (PJM)—is then paired with the nearest pricing node with substantial capacity (defined as any node with a substation having a voltage of more than 138 kV or associated with more than 200 MW of generation). Each of these nodes, in turn, is mapped to a specific ISO, ISO capacity zone (to estimate capacity value), and state (to estimate REC value, as well as reductions of both emissions and natural gas prices). Energy value is based on the wind plant’s hourly net output multiplied by hourly nodal real-time energy prices (aka, locational marginal prices, or LMPs). Capacity value is based on the wind plant’s capacity credit (estimated using each ISO’s rules in place at the time) multiplied by the ISO capacity zone’s prices. REC value is based on monthly Tier 1/Class 1 REC prices for each state multiplied by monthly net generation. We conduct a ‘marginal’ analysis, in effect assessing the value associated with the first offshore wind plants; some of the values estimated here would be expected to decline as offshore wind penetrations increase.

Elements Not Addressed in the Analysis

Several factors that may influence the value of offshore wind are not assessed in this analysis:

- The analysis does not account for any costs associated with the short-term variability (sub-hourly) and forecast error of offshore wind.
- Offshore wind value is estimated on the margin, assuming the addition of wind does not change the revenues for the wind plant. We do, however, separately estimate the effect of wind on consumer costs through the wholesale price ‘merit order’ effect.
- The wholesale price ‘merit order’ effect does not account for any local price suppression associated with congestion and losses. It also does not account for any potential reduction in forward capacity market prices.
- Avoided air emissions are quantified, and are valued in part through pollution permit prices embedded in LMPs and RECs; health and environmental benefits are not quantified.
- Avoided transmission costs are only addressed through the congestion component of the LMP prices.
- The analysis does not estimate the economic value or cost of other community and environmental effects (e.g., job creation, water use, tourism, property values, fishing impacts, etc.).

Wind sites that fall outside of the three organized ISO markets (i.e., those off the coast of most of North Carolina and all of South Carolina, Georgia, and Florida) are mapped to balancing areas (based on state boundaries) rather than to specific pricing nodes. In these instances, energy value is based on published ‘system lambdas’ (i.e., each balancing authority’s hourly estimate of marginal generating costs within its balancing area) rather than nodal pricing; capacity value is approximated based on capacity prices from the southernmost capacity zone in PJM and the capacity credit rules for PJM; and REC value is based on monthly Tier 1/Class 1 REC prices where they exist, or national voluntary REC prices in those states without an RPS (SC, GA, FL).

In addition to energy, capacity, and REC value (which, collectively, reflect the potential total market revenue of a merchant offshore plant, or the avoided costs for a purchaser of offshore wind), we also estimate the potential air emissions reductions associated with offshore wind, as well as the potential reduction in natural gas prices resulting from displaced gas-fired generation suppressing natural gas demand. For both purposes, we use the Environmental Protection Agency's (EPA's) AVOIDed Emissions and geneRation Tool (AVERT), which models electricity system dispatch on a regional basis (including for the three broad regions that encompass the U.S. East Coast) and, among other things, tracks both the emissions rate and natural gas consumption of generators estimated to be on the margin—and hence able to be displaced by offshore wind—in each hour. Finally, we estimate reductions in wholesale electricity prices resulting from the 'merit order' effect (i.e., low marginal cost offshore wind displacing higher-cost generation from the bid stack). It is important to recognize that these latter two effects—i.e., natural gas and wholesale electricity price suppression—are technically wealth transfers from gas producers and electricity generators to consumers. While some decision-makers consider these effects, others do not treat them as net societal "benefits" that create true economic value on a global basis.

Key Findings

Summary

We find that the average historical market value of offshore wind from 2007-2016—considering energy, capacity, and RECs—varies significantly by project location, from \$40/MWh to more than \$110/MWh, and is highest for sites off of New York, Connecticut, Rhode Island, and Massachusetts. As energy and REC prices have fallen in recent years, so too has the market value of offshore wind. The historical value of offshore wind is found to exceed that of onshore wind, due to offshore wind sites being located more favorably in terms of constrained pricing points, and also due to a more-favorable temporal profile of electricity production. Finally, we explore multiple ways to enhance the value proposition for offshore wind, including strategies associated with interconnecting to higher-priced locations and the addition of electrical storage. Whether any of these strategies, and offshore wind more generally, is economically attractive will depend on tradeoffs between value and cost. Cost reductions that approximate those witnessed recently in Europe may be needed for offshore wind to offer a credible economic value proposition on a widespread basis along the eastern seaboard.

The market value of offshore wind between 2007-2016 varies significantly by project location, and is highest for sites off of New York, Connecticut, Rhode Island, and Massachusetts. Figure 1 shows that the total market value (i.e., energy, capacity, and REC value combined) of offshore wind is highest for sites off of New York, Connecticut, Rhode Island, and Massachusetts; lower for projects off of Maine; and lowest elsewhere along the coast. When averaged over the entire 2007-2016 period (left half of Figure 1), the median marginal value for sites interconnecting to ISO-NE is roughly \$110/MWh, compared to \$100/MWh for sites interconnecting to NYISO, \$70/MWh for sites in PJM, and closer to \$55/MWh for sites in the non-ISO region south of PJM. When focusing on just 2016 (right half of Figure 1), the corresponding marginal values are much lower (for reasons explained later), but the relative differences across states and regions is still similar. The median value for sites in ISO-NE is \$70/MWh in 2016, and for NYISO is nearly \$65/MWh. The median value of sites in PJM is \$45/MWh, while it is less than \$40/MWh for sites in the Non-ISO region south of PJM. Of course,

just as the market value of offshore wind varies spatially, so too does the levelized cost of offshore wind energy (LCOE), affected by wind speed, ocean depth, distance from shore, and many other considerations. Comparing LCOE estimates with value estimates, we find that the most attractive sites from this perspective are located near southeastern Massachusetts and Rhode Island, while the least attractive are far offshore of Florida and Georgia.

The market value of offshore wind can be approximated by the value of a flat block of power; the locational variation in the market value of offshore wind is driven primarily by differences in average energy (and REC) prices across pricing nodes, states and regions, rather than by differences in diurnal and seasonal wind generation profiles across project sites. This insight is revealed by comparing a site's total market value based on wind resource availability (i.e. the left panel of Figure 1) to a hypothetical value created at each site by calculating the simple average energy, capacity, and REC prices *across all hours* (a 24x7 'flat block' of power).¹ In other words, Figure 2 compares the marginal revenue earned by each offshore wind project to the amount of revenue it would have earned if generating the same total amount of annual energy but with no temporal variation in output. The resulting 'normalized' market value (total, energy, and capacity, respectively, from left to right) of offshore wind shown in Figure 2 indicates whether offshore wind is more or less valuable than a 24x7 flat block of power; variation in this metric across sites solely reflects differences in diurnal and seasonal generation profiles.

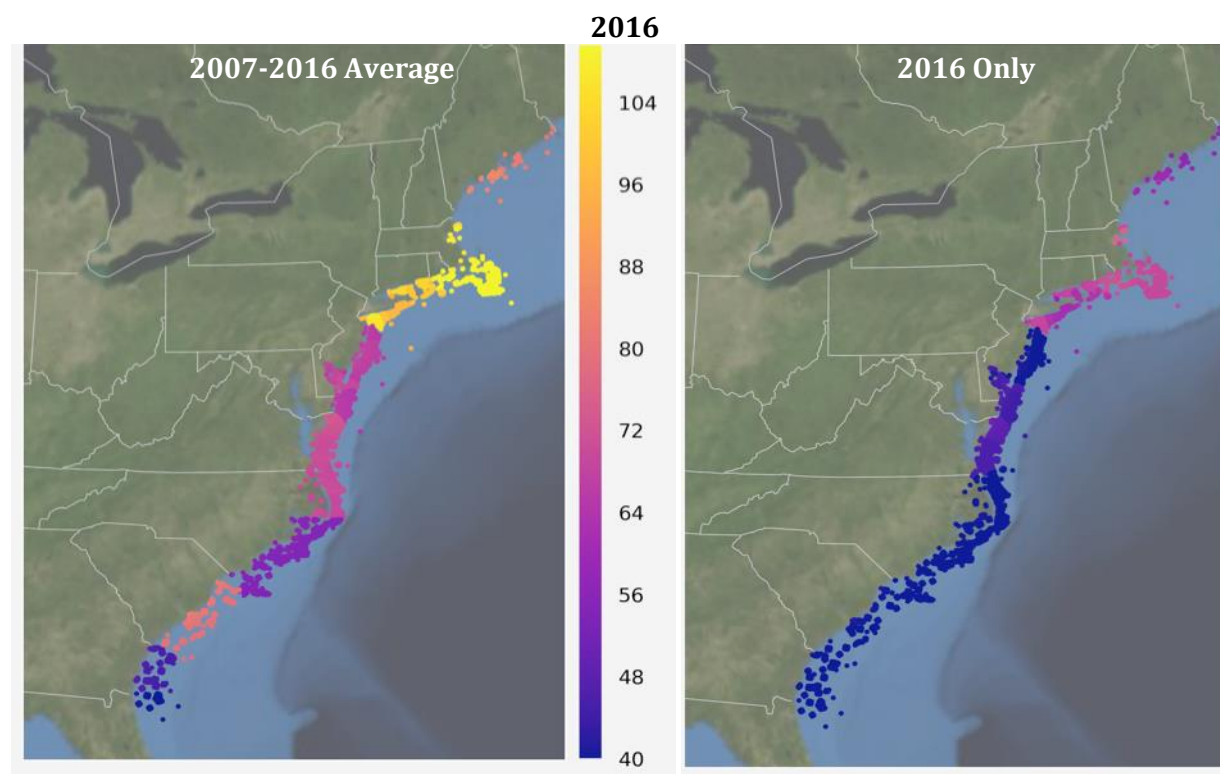


Figure 1. Total market value (energy + capacity + REC) at each site, averaged over 2007-2016 (left) and for 2016 only (right)

¹ In this analysis, REC value is assumed to vary on a monthly, but not hourly, basis. Hence, REC value across sites is not at all affected by differences in diurnal generation profiles.

As shown, the normalized total market value of offshore wind (left pane) ranges from 95%-105%, with somewhat larger ratios found in NYISO, ISO-NE, and off the coast of North Carolina. The energy value component (middle pane) tells a similar story, and with a similarly modest range (98%-108%). In contrast, the normalized capacity value component (right pane) varies more significantly, from 50%-120% (capacity value is explored further in the next key finding). The rather modest ranges for both total and energy value indicate that variability in wind generation profiles across sites is not a strong determinant of offshore wind market value along the East Coast; instead, the significant variation in market value seen in Figure 1 is driven much more by local energy (and REC) prices. The market value of offshore wind is roughly similar to that of a similarly located flat block of power, at least on a marginal basis for the first offshore wind plants.

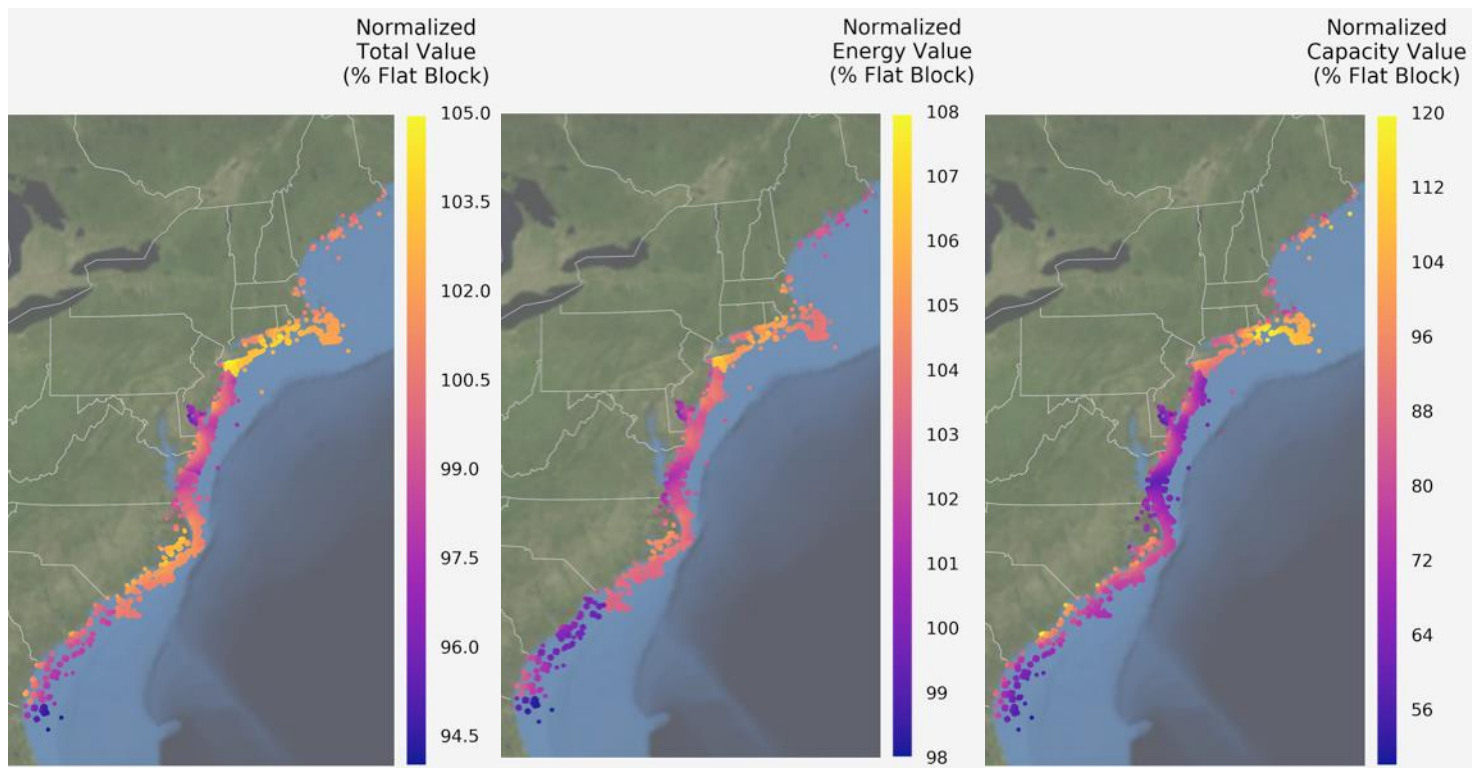


Figure 2. Normalized total market value and its energy and capacity components

Diurnal and seasonal generation profiles do matter, but mostly for capacity value, which is a small component of overall value. The relatively wide range (50%-120%) in normalized capacity value shown in the right pane of Figure 2 solely reflects differences in wind generation profiles across sites (as well as the rules by which wind plants earn capacity payments), with sites off of Rhode Island and Massachusetts having the most advantageous profiles in terms of aligning with capacity measurement periods. Similarly, winter capacity credits are highest for the areas off of Rhode Island and Massachusetts (see Figure 3). Figure 3 also shows the distribution of summer capacity credit along the entire east coast. Note that winter capacity credits are shown for NYISO and ISO-NE sites only, as PJM does not assess capacity credits in the winter (we assume that PJM capacity market rules apply to all states south of PJM). The capacity credit of offshore wind in the NYISO and ISO-NE markets is significantly higher in winter than in summer; offshore wind in these regions benefits from having capacity credit assessed in both seasons. While there is significant variation in

capacity credit (Figure 3) and normalized capacity value (Figure 2) across sites, capacity value is a relatively minor component of the total market value of offshore wind, as shown in Figure 4.

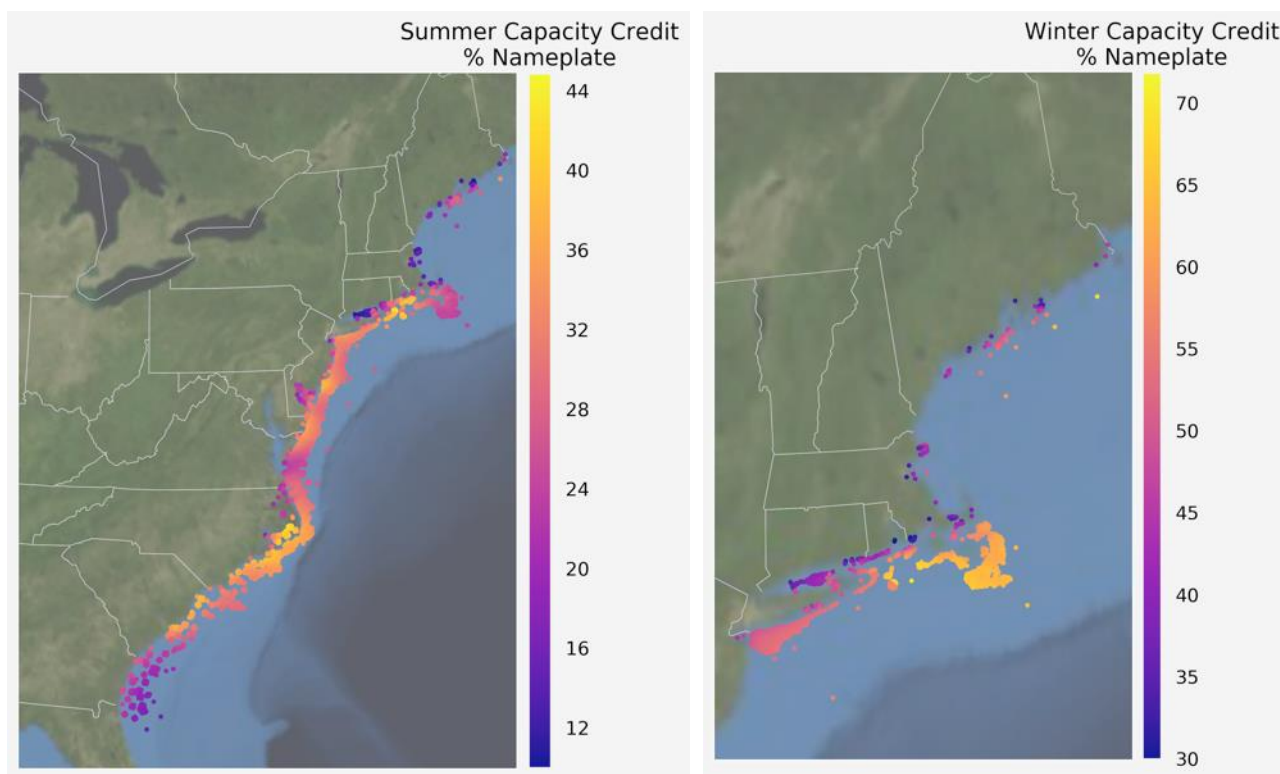


Figure 3. Capacity credit in summer and winter

In addition to varying geographically, the market value of offshore wind also varies significantly from year to year, driven primarily by changes to energy and REC prices; the market value of offshore wind is lowest in the most recent year evaluated—2016. This inter-year variation was first seen in Figure 1, where the total market value of offshore wind in 2016 was significantly lower than the value averaged over 2007-2016. Figure 4 shows that this significant decline in total market value is attributable primarily to lower electricity prices in 2016, which reduced the median energy value of offshore wind to ~\$30/MWh across all four regions. Figure 4 also confirms that the capacity value of offshore wind is only a small component of total value. Variability in total market value over time has been driven by both electricity and REC prices (with the former heavily influenced by natural gas prices). The total market value is highest in ISO-NE, in part due to higher REC prices. The energy and capacity value is higher for NYISO, particularly for the Long Island region.

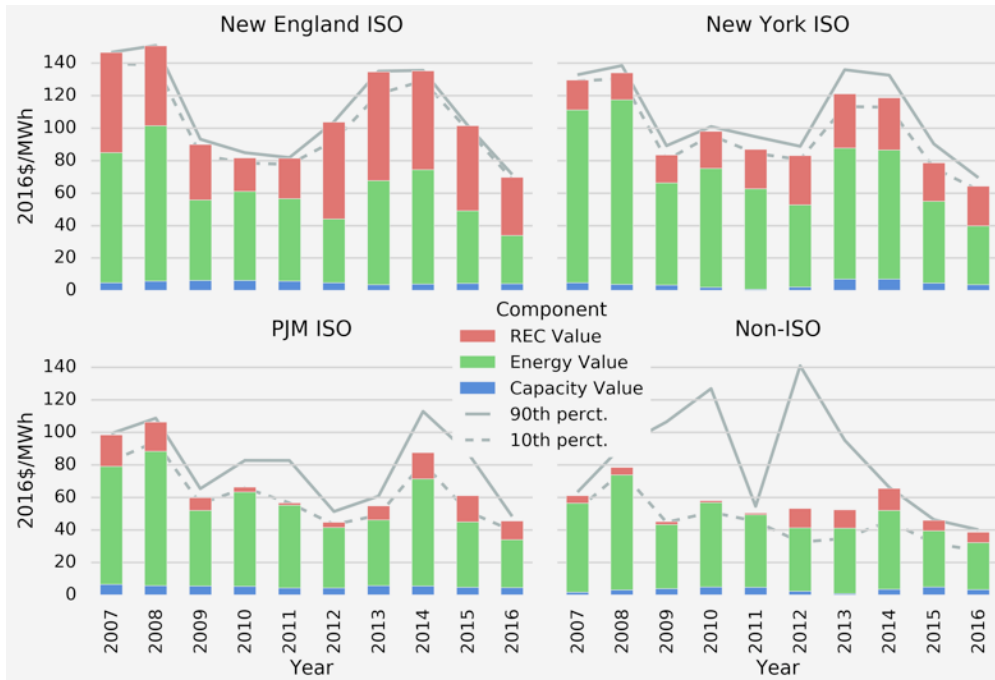


Figure 4. Median energy, capacity, and REC value by year for sites within each region. The lines show the 10th (dashed) and 90th (solid) percentile of the total market value across all sites within each region.

The energy and capacity value of offshore wind in all three ISOs exceeds the value of onshore wind. Figure 5 shows that, in 2016, the total marginal energy and capacity value of offshore wind would have exceeded the value of existing onshore wind by \$6/MWh in ISO-NE (21% higher), \$6/MWh in PJM (24% higher), and by more than \$20/MWh in NYISO (112% higher). The differences in energy and capacity value between onshore and offshore wind is due to differences in location and differences in hourly output profiles: location appears to play a somewhat larger role than output profile, in most cases. The estimated summer and winter capacity credit for offshore wind in the three ISOs is roughly double that for onshore wind.

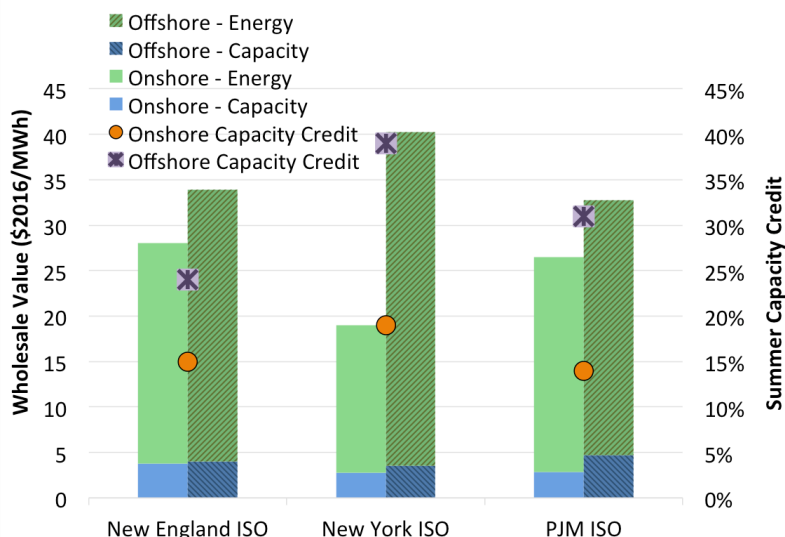


Figure 5. Comparison of 2016 energy and capacity value for offshore and onshore wind

Offshore wind reduces air emissions that are harmful to human health and the environment, yet the avoided emissions rate for pollutants like SO_2 has declined over time. Figure 5 shows that avoided emissions attributable to offshore wind vary by region—highest in the Mid-Atlantic, lower in the Southeast, and lowest in the Northeast²—and have generally declined over time, as the emissions rate of the marginal generator has improved. The decline has been particularly steep for SO_2 (top left graph), as coal plants have either retired or installed pollution control equipment. Although avoided emissions is a measurable benefit of offshore wind, the economic value of avoided emissions is not necessarily additive to the energy, capacity, and REC value discussed earlier; this value is already embedded in energy value to some degree, since pollution permit prices are reflected in locational marginal prices (LMPs). One could argue that REC value similarly reflects the benefits of avoided emissions. That being said, studies have found that recent air quality benefits from wind power in these regions ranges from \$26/MWh to >\$100/MWh, depending on the location of the wind project; at the upper end, these values exceed the value reflected in RECs.

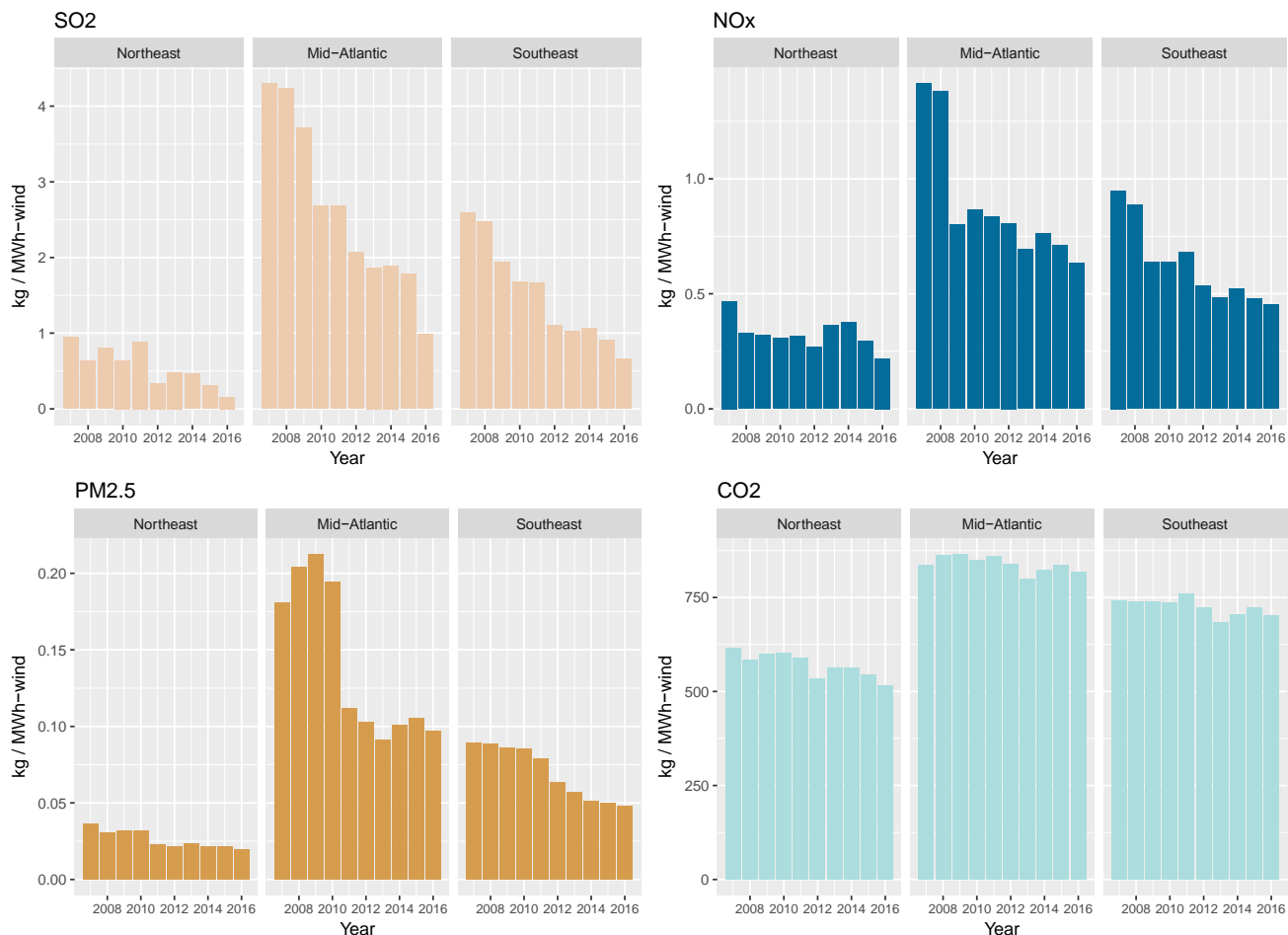


Figure 5. Avoided SO_2 (top left), NO_x (top right), $PM_{2.5}$ (bottom left), and CO_2 (bottom right) emissions rate by year for average offshore wind profile in each region

² The three AVERT regions do not perfectly align with the four market regions discussed elsewhere. For example, AVERT's Northeast region encompasses both the NYISO and ISO-NE regions, while its Great Lakes-Mid-Atlantic region includes most of PJM but also additional states.

Wholesale electricity and natural gas price reductions attributable to offshore wind can be substantial, though these price reductions represent a wealth transfer between producers and consumers. When the marginal generation unit displaced by offshore wind is a gas-fired generator, offshore wind not only avoids emissions but also reduces the consumption of natural gas. Because natural gas supply is relatively inelastic in the short term, reductions in natural gas demand can lead to price reductions, resulting in flow-through consumer benefits in the form of lower natural gas expenditures throughout the economy. For example, we estimate that natural gas price savings nationwide could have an equivalent value per-MWh of offshore wind of \$30-\$80/MWh of offshore wind averaged over 2007–2016, depending on in which region the offshore wind is located. Local regional price savings in the region in which the offshore wind plant interconnects are significantly lower, but still significant, at less than \$6/MWh of offshore wind (Figure 6). Similarly, low-marginal-cost offshore wind also reduces wholesale electricity prices by displacing the highest-cost marginal generating units from the bid stack. When translated to an equivalent consumer benefit per-MWh of offshore wind, we estimate this ‘merit order effect’ to be more than \$25/MWh averaged over 2007–2016 in all three ISO regions, and significantly lower in the states south of the PJM region (Figure 6). The natural gas and wholesale electricity price suppression effects are lowest in 2016.

These natural gas and wholesale price reductions, however, represent a transfer of wealth from natural gas producers and electricity generators to gas and electricity consumers, respectively. While some decision-makers are interested in natural gas and wholesale price reductions, not all consider them to be net societal benefits. Moreover, these price suppressing effects would be anticipated to decline over time, as supply adjusts to the new demand conditions.

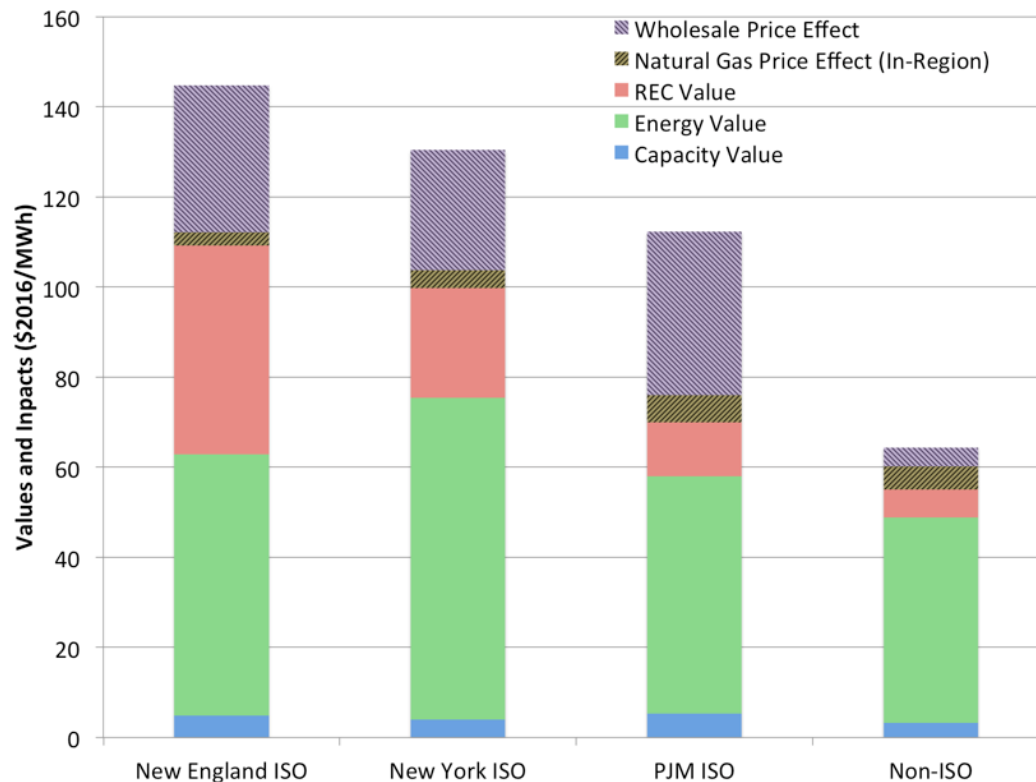


Figure 6. Median energy, capacity, and REC value along with the in-region natural gas price effect and wholesale electricity price effect averaged over 2007-2016

Outside of the confines of our base-case analysis, we explored—and found—several other ways to enhance the value of offshore wind. Interconnecting to a more-distant but higher-priced node can increase the value of offshore wind by as much as \$25/MWh, particularly when switching from PJM or ISO-NE nodes to NYISO nodes around Long Island. Even better, having more than one interconnection point and arbitraging between them can increase value by \$40/MWh-wind in some cases. Selling RECs into a different state than the one in which the project interconnects can add up to \$20/MWh of value beyond our base-case assumptions, depending on the location. Adding battery storage sized (in MWh terms) at roughly one fourth of the offshore wind project capacity can increase value by up to \$3/MWh-wind, with still-greater incremental value as battery size increases. Finally, wind turbine design is found to have a minor effect on market value, at least for the first offshore wind projects installed in a region.

Future Outlook

This analysis is backward-looking, focused on historical wind patterns and market outcomes from 2007-2016 in order to estimate the hypothetical marginal value of offshore wind along the U.S. east coast (i.e., had any such projects been operating during this time period). Though this marginal, historical perspective is instructive in terms of identifying key value drivers, the decision to build offshore wind going forward will depend on expectations of *future* benefits, which may differ from recent historical experience. With that in mind, we conclude by qualitatively assessing the outlook for some of the value drivers identified in this paper; many of these outlooks remain highly uncertain.

- Energy value—the largest value component within our analysis—will partly depend on the future direction of natural gas prices, which is highly uncertain. For example, the Energy Information Administration (EIA) projects gas prices to drift higher over time, while NYMEX natural gas futures suggest medium-term price reductions. Several projections of electricity prices in the ISO-NE, NYISO, and PJM areas show significant variation across forecasts, but a general upward trend. Finally, increasing wind penetration over time could drive down wind's energy value in the future, as the market becomes saturated with low marginal-cost wind power during windy times; such a value decline has been observed in high-penetration wind markets internationally.
- REC prices—another significant contributor to offshore wind's value—will depend in part on the cost and value of alternative means of complying with state RPS requirements. As the cost of wind and solar power continues to decline, one might expect to see declining REC prices as well. On the other hand, some states have established, or could establish, specific offshore wind obligations, which could boost the value of offshore wind RECs.
- Offshore wind's capacity value depends on capacity prices, the rules for how capacity credit is determined, and whether offshore wind is eligible to participate. Capacity prices are generally expected to increase in the future, but several proposed or pending market reforms may make it more difficult for offshore wind to participate in capacity markets.

- Avoided emissions should remain around recent levels, barring either regulatory rollback or implementation of new and more-stringent emissions targets. Higher natural gas prices, however, could potentially shift the dispatch towards more coal-fired generation, potentially increasing avoided emissions. On the other hand, such a shift in the supply curve might lead to more gas-fired generation on the margin, which would reduce offshore wind's avoided emissions, thus it is hard to predict the exact effect on avoided emissions due to any future increase in gas prices.
- The degree to which offshore wind suppresses natural gas and wholesale electricity prices will depend in large part on the level of natural gas and wholesale electricity prices going forward—both of these have been discussed already above. This analysis focused on first-year or short-term effects. The effects are generally expected to decline over time, as supply adjusts to the new demand conditions.

Some of these and other issues will be assessed in forthcoming work from NREL³, which will model several offshore wind scenarios in a future U.S. power system (years 2024 and 2038) within the NYISO and ISO-NE market regions, focusing on performance metrics including reliability, capacity value, transmission needs, production cost savings, wholesale price suppression, curtailment levels, and system ramping needs.

³ Beiter et al. 2018 (forthcoming). *Assessing the Value of Offshore Wind: A Grid Modeling Analysis*. Golden, Colorado: National Renewable Energy Laboratory.

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